Pulsar Timing Arrays (PTA): an update

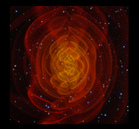
Bruce Allen
Max Planck Institute for Gravitational Physics
(Albert Einstein Institute, AEI)
Hannover, Germany

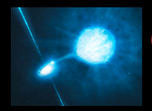
References

- Hellings and Downs, "*Upper limits on the isotropic gravitational radiation background from pulsar timing analysis*", ApJ, 265 (1983)
- Allen, "*Will pulsar timings arrays observe the Hellings and Downs curve?*", Frascati Phys. Ser. 74, 65-80 (2022)
- Allen, "*Variance of the Hellings and Downs correlation*", PRD 107, 043018 (2023)
- Allen and Romano, "*Hellings and Downs correlation of an arbitrary set of pulsars*," PRD 108, 043026 (2023)
- Agazie et al., "*The NANOGrav 15 yr data set: Evidence for a gravitational-wave background*", ApJ Letters, 951:L8, (2023)
- Agazie et al., *"Comparing recent PTA results on the nanohertz stochastic gravitational-wave background",* ApJ 966:105 (2024)
- Romano and Allen, "*Answers to frequently asked question about the pulsar timing arrray Hellings and Downs correlation curve*", to appear in CQG (2024)

Big Bang

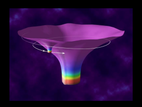
Supermassive Black Hole Binary Inspiral & Merger



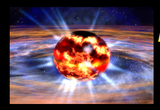


Compact Binary Inspiral & Merger

Sources



Extreme Mass-Ratio Inspirals



Pulsars, Supernovae

The Gravitational Wave Spectrum

age of the universe

years

Wave Period

hours

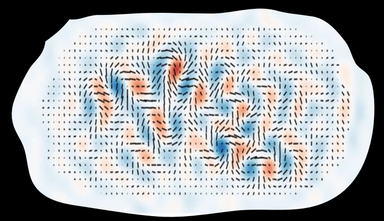
seconds

milliseconds

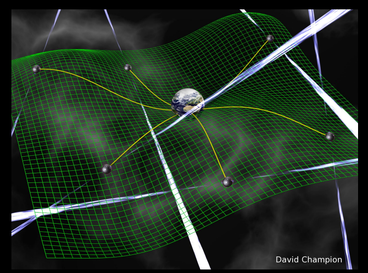
-16 -14 -12 -10 -8 -6 -4 -2 0 +2

log(f)

CMB Polarization

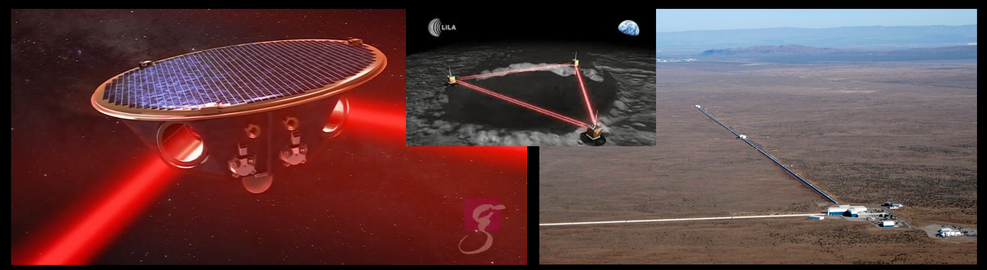


Radio Pulsar Timing Arrays



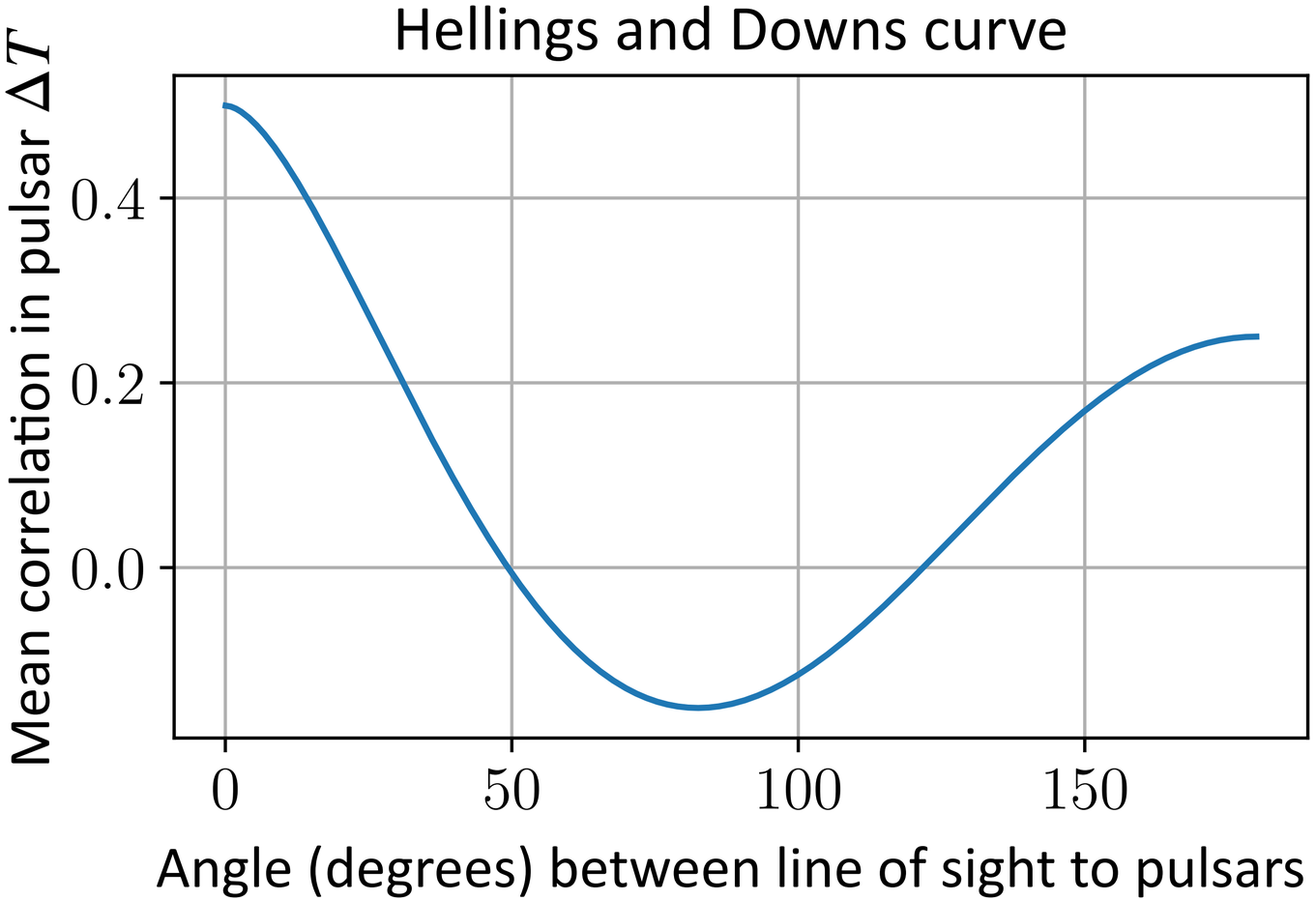
Space-based interferometers

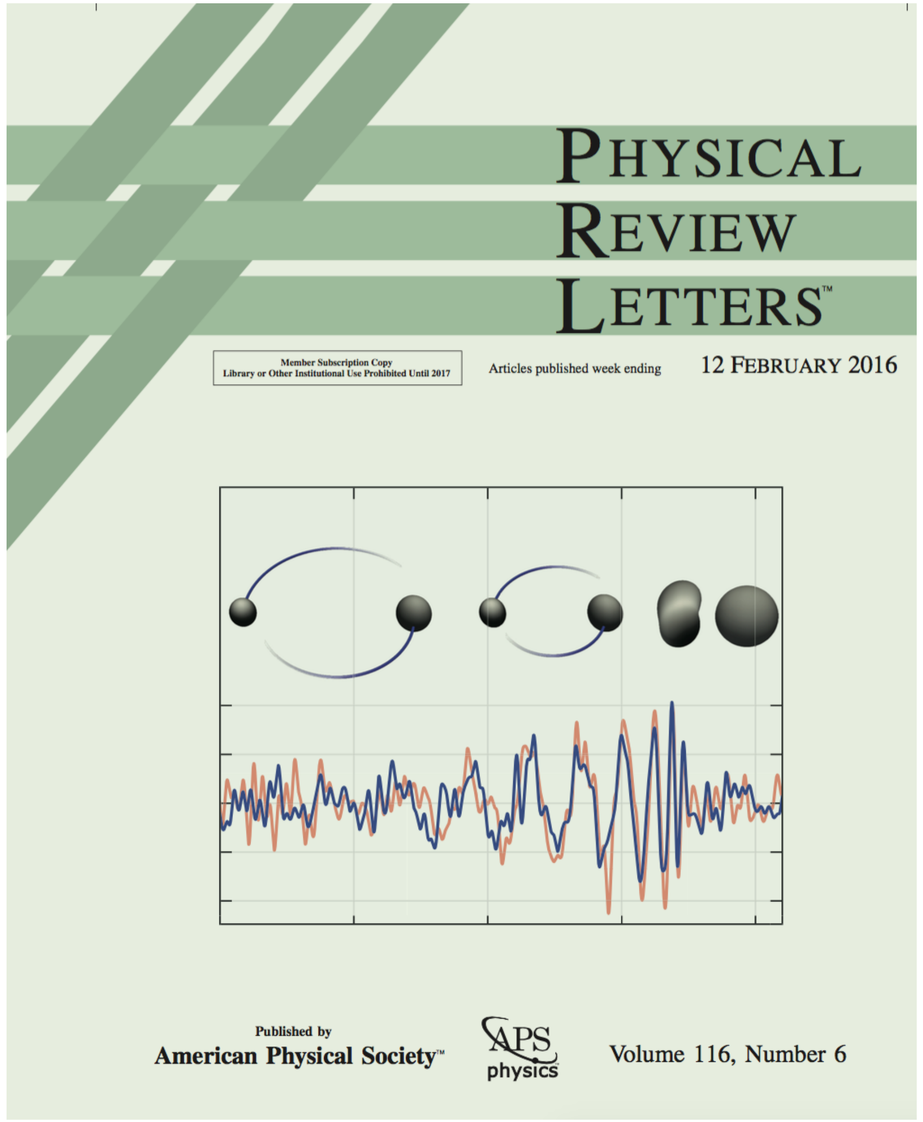
Terrestrial interferometers



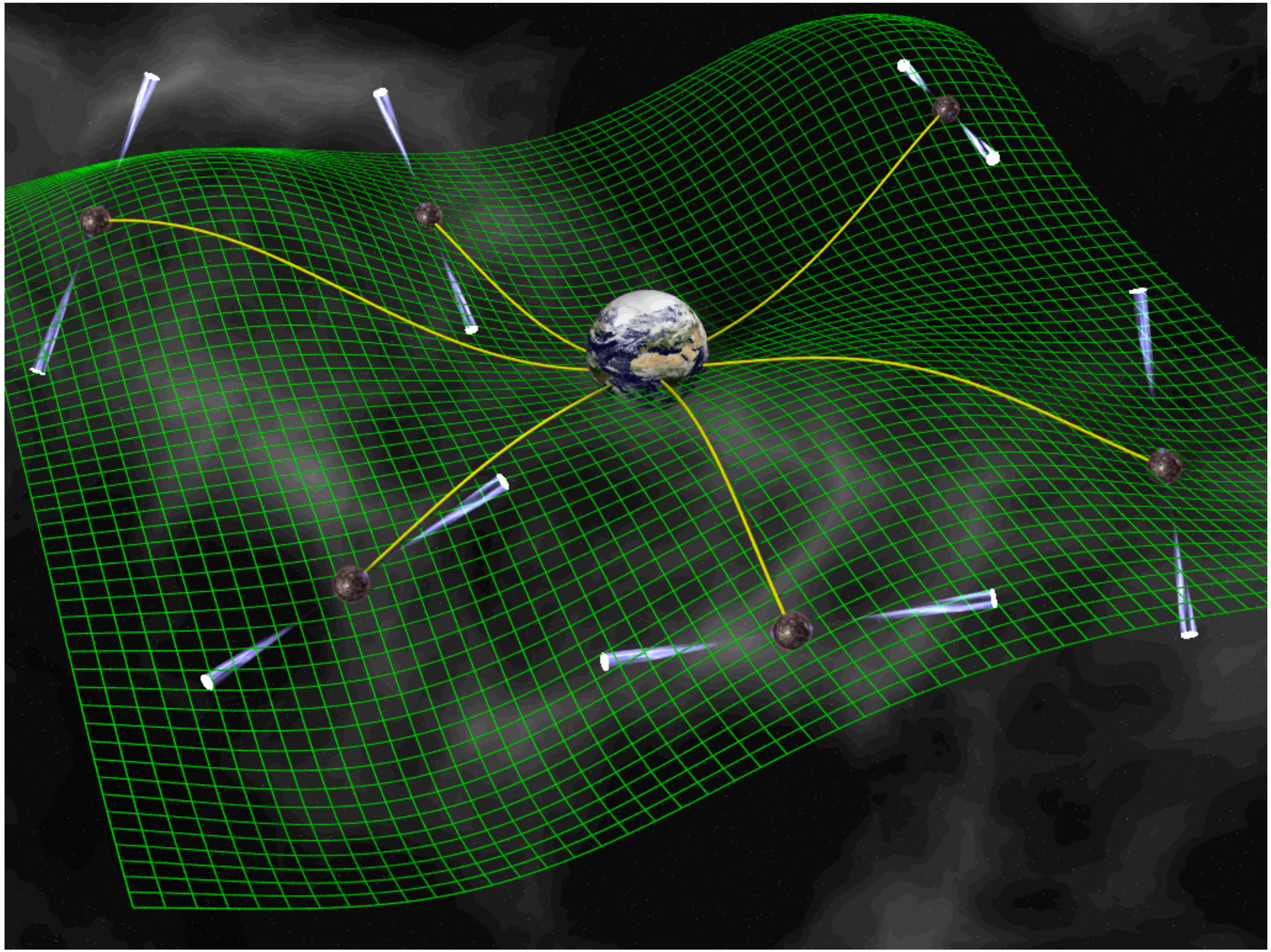
Detectors

Hellings and Downs curve
For PTAs, like LIGO/Virgo binary “chirp” waveform

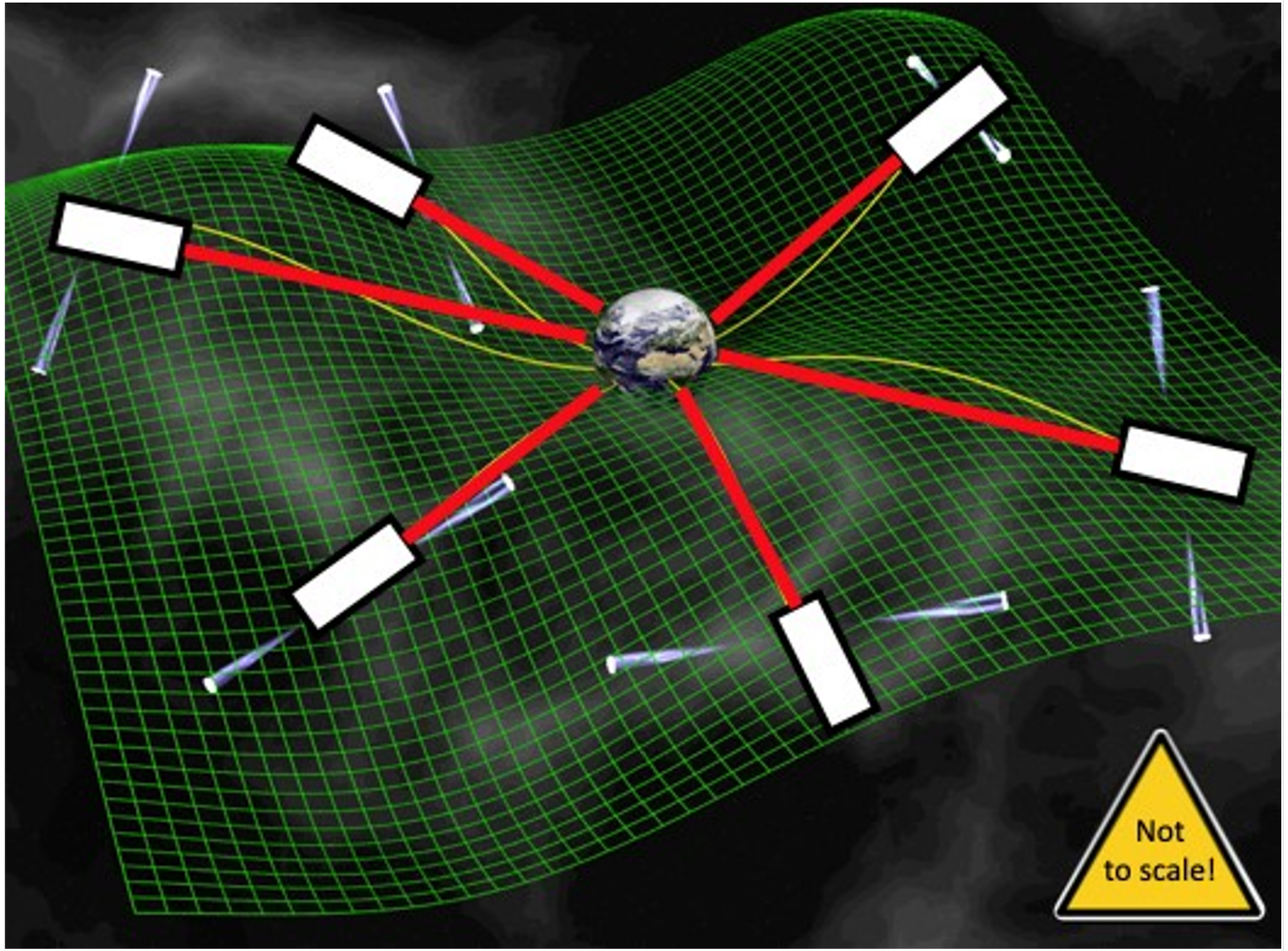




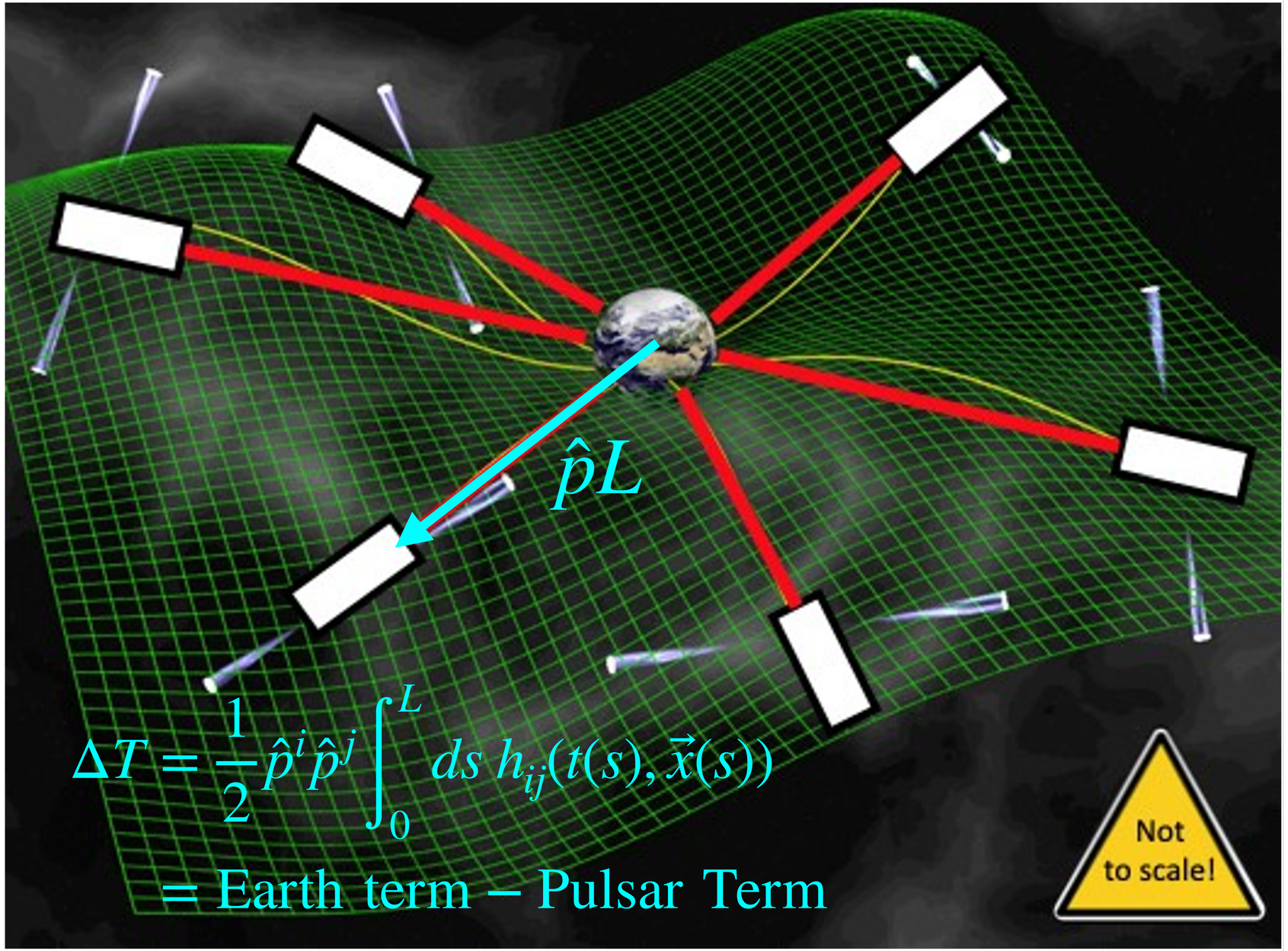
Pulsar Timing Arrays (PTA)



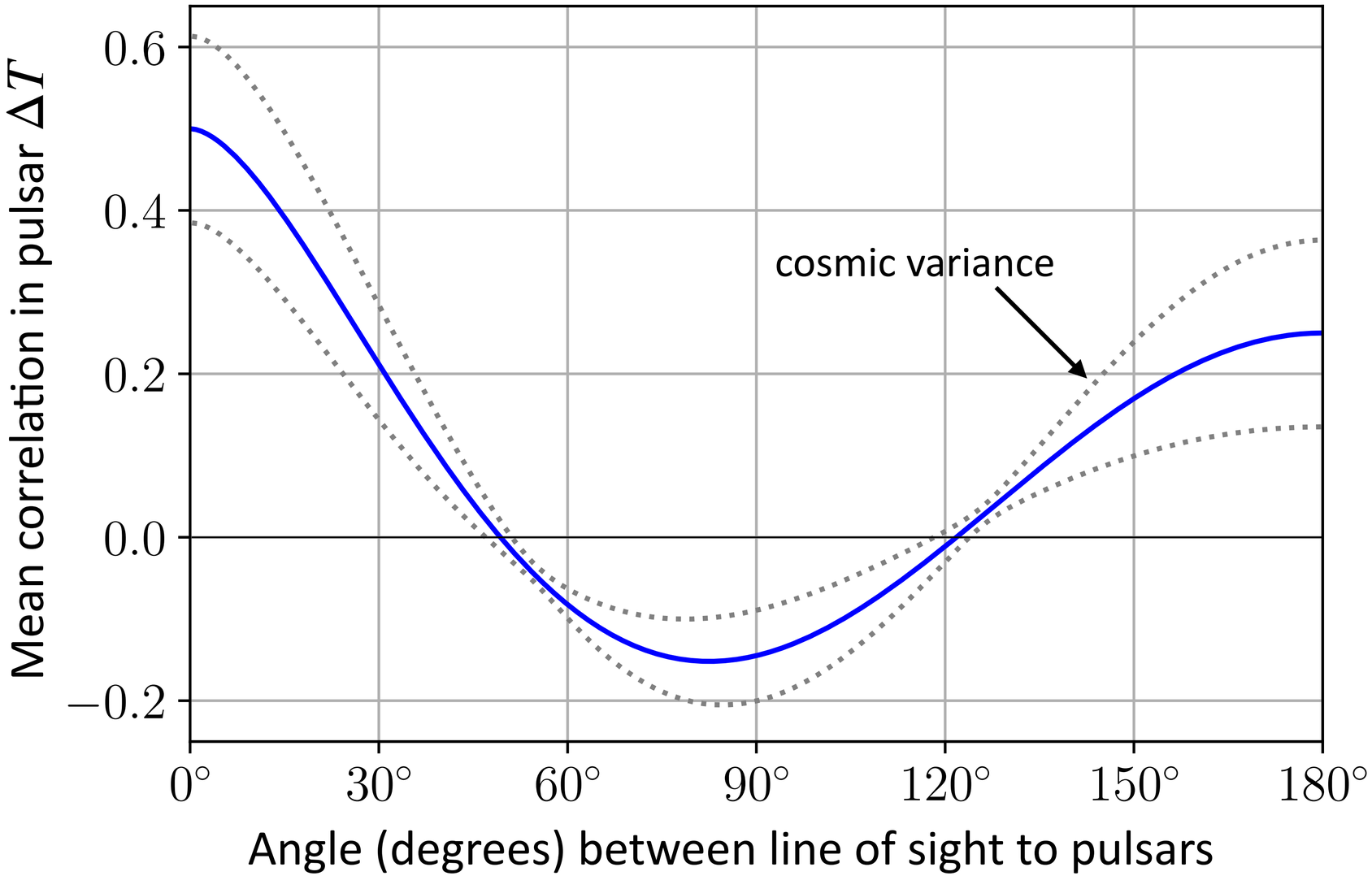
Pulsar Timing Arrays (PTA)



Pulsar Timing Arrays (PTA)



Hellings and Downs corrrelation



Latest results from four PTAs published 29.6.2023

1. Chinese Pulsar Timing Array CPTA, Res. Astron. Astrophys. 23, 075024 (2023), 57 pulsars over 3 years, *"Some evidence"*

2. Parkes Pulsar Timing Array PPTA, ApJL 951 L6 (2023), 24 pulsars over 18 years, *No support for or against*

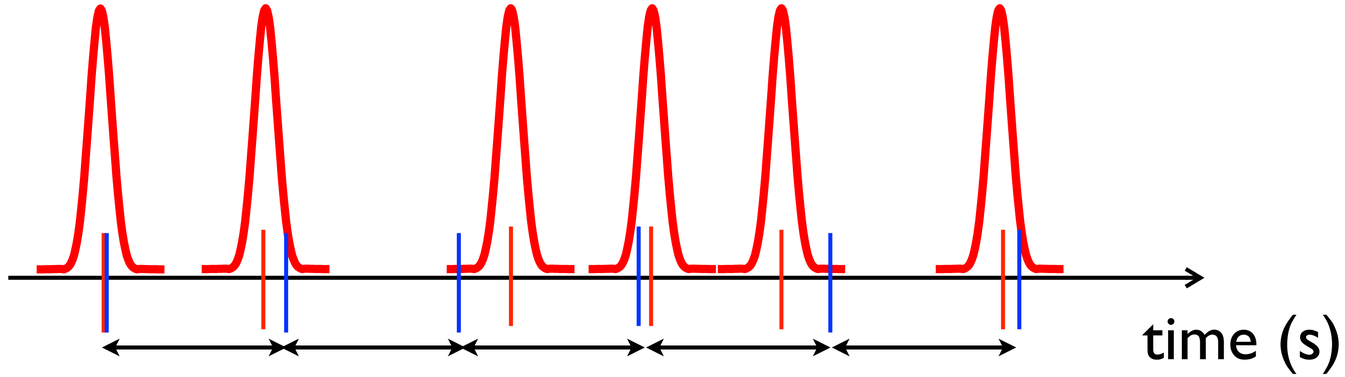
3. European Pulsar Timing Array EPTA, arXiv:2306.16214, Astron. Astrophys. (2023), 42 pulsars over 25/10 years*, "Marginal evidence/evidence"*

4. North American Nano-Hz Observatory for Gravitational Waves NANOGrav, ApJL 951, L8 (2023), 67 pulsars over 15 years, *"Compelling evidence"*

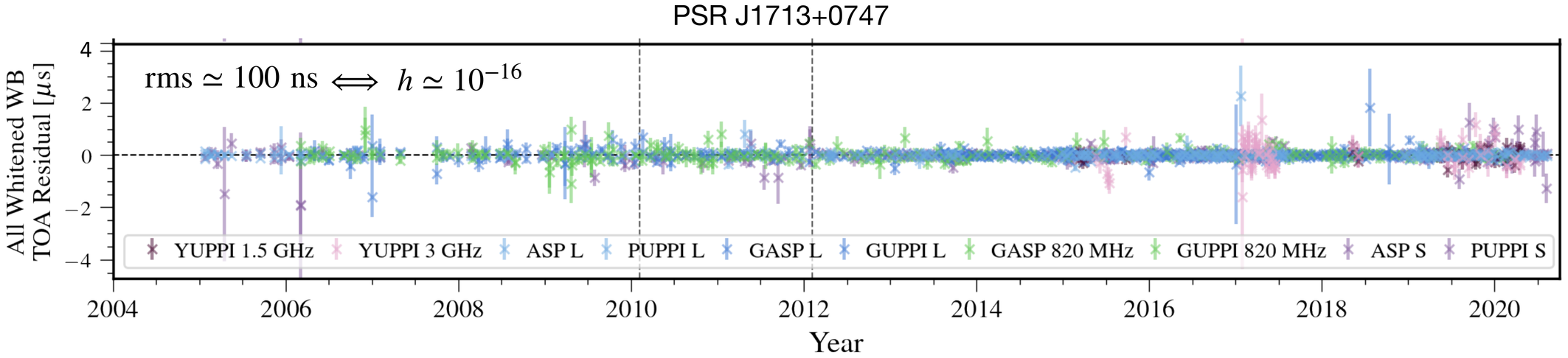
First joint analysis of three PTAs published 6.9.2023

5. International Pulsar Timing Array (IPTA) comparison of 2, 3, and 4 above, ApJ 966 105 (2024): *Data from three PTA are consistent with a single "joint" stochastic gravitational wave background amplitude and power spectrum*.

PTA data: timing residuals



$$\text{timing residual} = \text{observed arrival} - \text{predicted arrival}(\alpha, \delta, f, \dot{f}, \ \ldots)$$
$$= \text{errors in timing model} + \text{noise} + \text{gravitational waves}$$



PTAs consider different signal & noise models

Pulsar 1

Timing Model
Measurement noise
Intrinsic pulsar noise

+

Pulsar 2

Timing Model
Measurement noise
Intrinsic pulsar noise

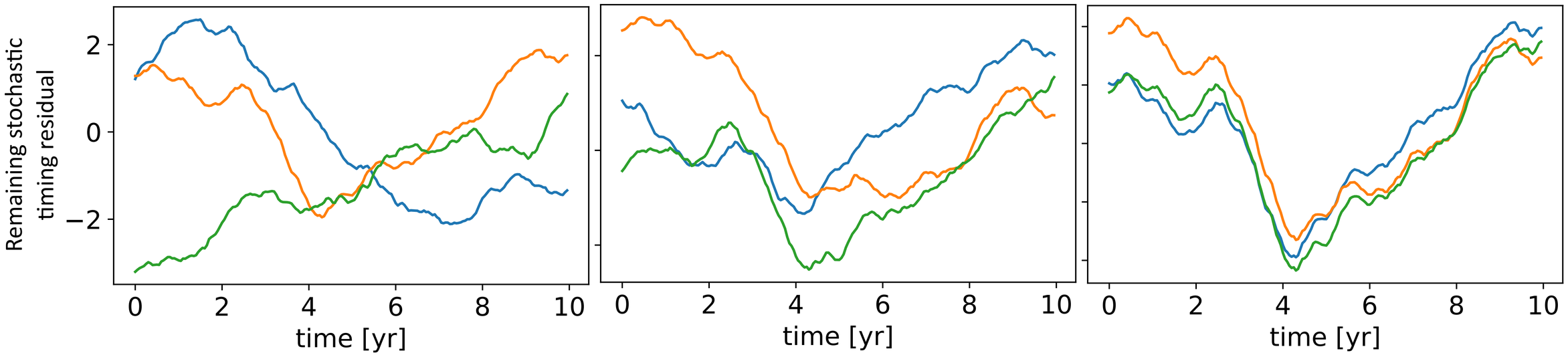
+ … +

Pulsar N

Timing Model
Measurement noise
Intrinsic pulsar noise

+

Remaining stochastic process:
if gravitational wave background, then correlated across all pulsars)

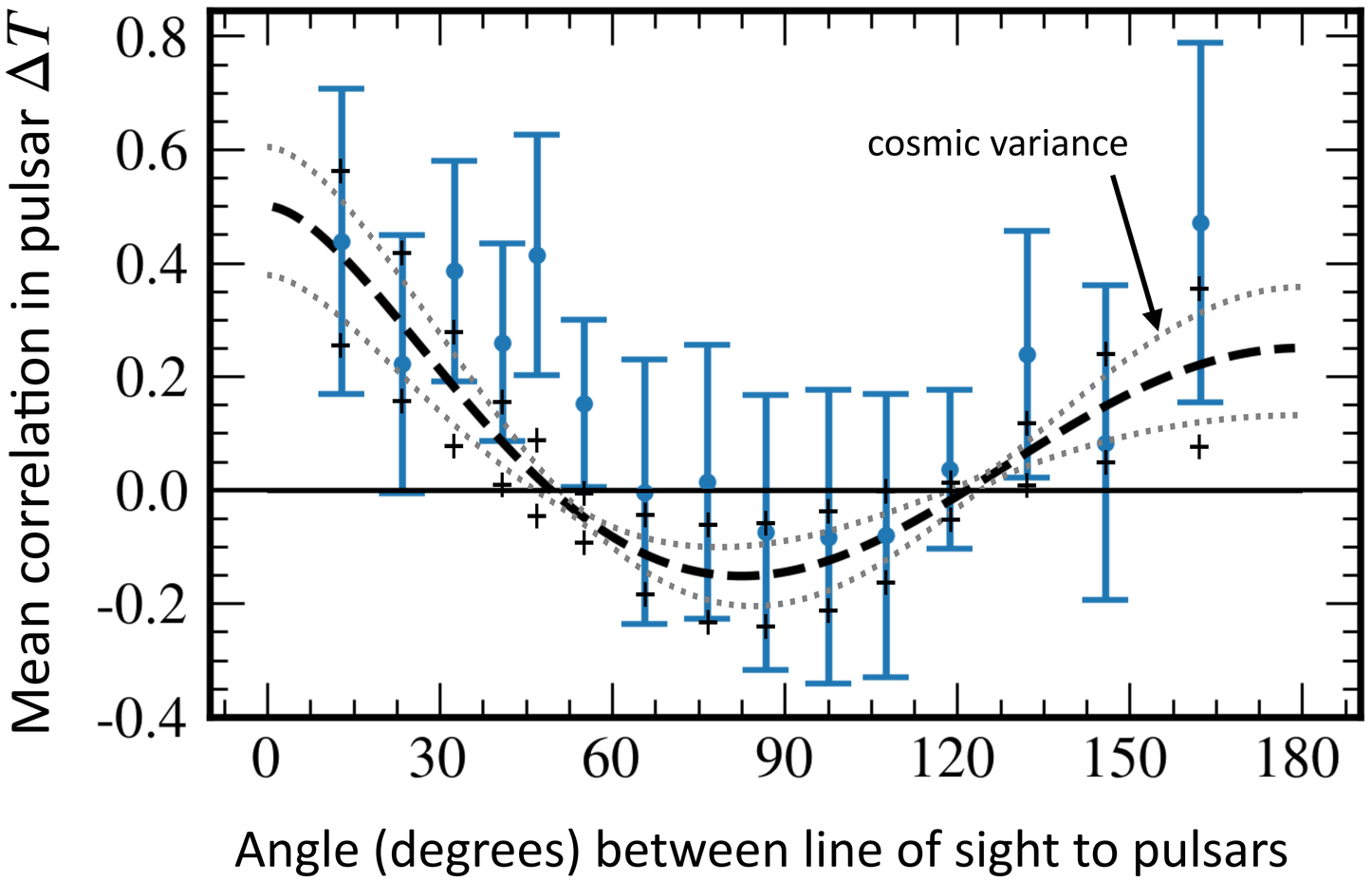


uncorrelated

moderate correlations (50%)

strong correlations (95%)

NANOGrav observed correlations



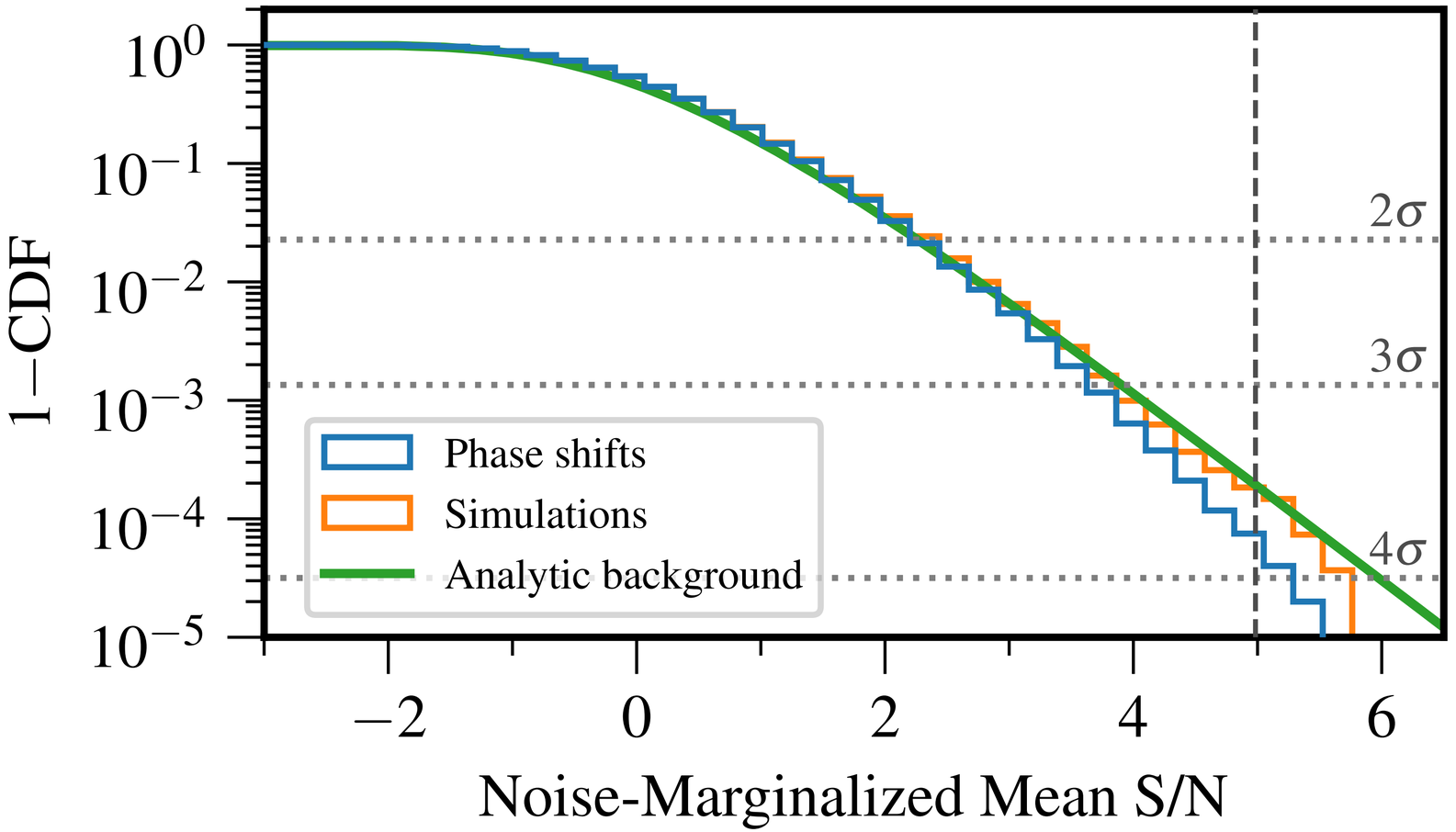
$$\frac{67(67-1)}{2} = 2211 \text{ pulsar pairs}$$

$$\frac{2211}{15} \approx 147 \text{ pairs/angle bin}$$

Point estimates: (weighted) averages of the inter-pulsar correlations in each bin

Data are correlated across pulsars as expected for a GW backgound

NANOGrav's detection confidence



$$\mathrm{S/N} = \frac{\sum_{a<b} \rho_{ab} \Gamma_{ab} / \sigma^2_{ab,0}}{\sqrt{\sum_{c<d} \Gamma^2_{cd} / \sigma^2_{cd,0}}}$$

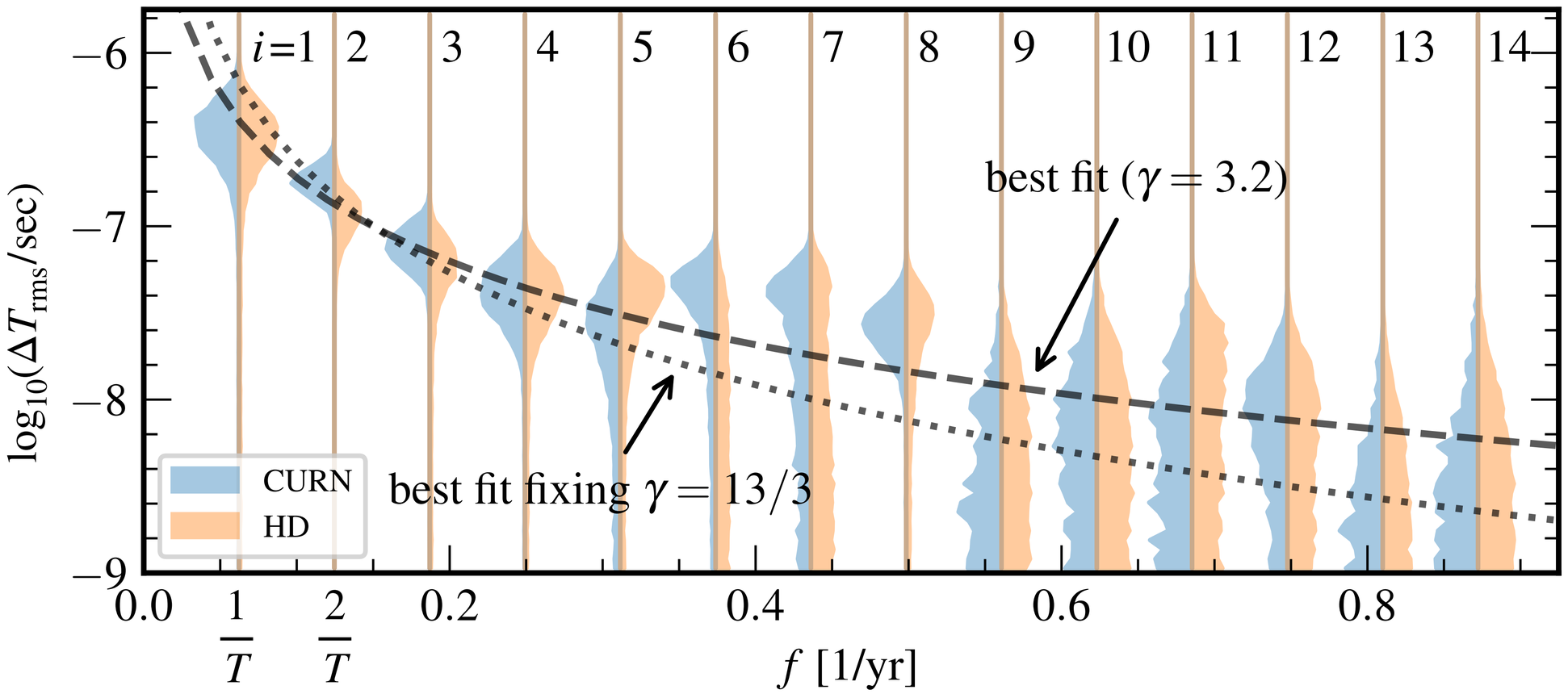
- Noise-weighted inner product of inter-pulsar correlations ρ_{ab} with expected HD correlations Γ_{ab} (like a matched filter statistic)
- Zero mean, unit variance in absence of a correlations; but not a gaussian

Detection statistic value unlikely due to uncorrelated noise alone because probability $\approx 10^{-4}$: **"compelling evidence"** (but not a detection)

Summary

1. There is evidence for a correlated stochastic GW signal in recent PTA data.
2. The correlations follow the predicted “Hellings and Downs” pattern expected for a GW background.
3. A population of super-massive binary black holes associated with galaxy mergers fits the data, but so do other possible gravitational wave sources.
4. Results generally consistent across PTA collaborations. International Pulsar Timing Array (IPTA) consortium should analyze the full data set (~115 pulsars, ~25 yrs) within coming year.
5. Power spectrum of gravitational wave background (rising at low frequency) means that the coming years should see great improvements in ability to characterize this background.

NANOGrav's observed common power spectrum



$T = 16.03$ yr

$\gamma = 13/3$ (binary inspiral)

$A = 2.4^{+0.7}_{-0.6} \times 10^{-15}$

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f} = 7.4 \times 10^{-9} \left(\frac{f}{1/{\rm yr}}\right)^{2/3}$$

Observed common power spectrum consistent with predictions from a population of SMBH binaries, and also many other GW source models!!